4D MRI AS THE BEST WAY TO PRESCRIBE PATIENT-SPECIFIC PROXIMAL AND DISTAL BOUNDARIES FOR NUMERICAL MODELING

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Introduction

Time-resolved phase-contrast magnetic resonance velocimetry (4D MRV) is capable of acquiring three-dimensional velocities in vivo. However, the limited spatial resolution of this method, particularly in near-wall regions, can lead to errors in estimation of wall shear stress (WSS) – an important hemodynamic descriptor related to vascular disease progression. An accurate estimation of WSS can be obtained in patient-specific computational fluid dynamics (CFD) models with refined meshes, constructed from MRI data. In order to ensure CFD modeling accuracy it is important to prescribe appropriate proximal and distal flow boundary conditions (BC's). State of the art CFD relies on low-order models and various assumptions in order to account for the effect of distal vasculature. In this study we have used 4D MRV data to prescribe BC's for CFD simulations and compared these results to computations carried out based on specific different assumptions about the distal circulation.

Methods

Two cases were considered in order to evaluate the effect of the outlet boundary conditions: a basilar artery aneurysm and an arteriovenous fistula. In both cases, numerical simulations were carried out for three distal flow scenario: the flow through the outlets calculated from in vivo 4D MRV measurements; the outlet flow specified from assumptions about the distal vascular territories; and with equal pressure prescribed at all outlets. Contrast enhanced MRA data were acquired to obtain luminal geometries for the CFD modeling. The flow fields in the vessels were measured in vivo with 4D MRV. The governing flow equations were solved numerically with a finite-volume package, FLUENT (ANSYS, Inc, Canonsburg, PA). The velocity and WSS fields computed in simulations with different BC's were compared.

Results

In the first case, the posterior cerebral arteries (PCA's) emanating from the basilar tip aneurysm were very different in size. The flow streamlines obtained from in vivo 4D MRV are shown in Fig. 1.a. The WSS distribution obtained in computations with the outlet BC's measured from this 4D MRV data is shown in Fig. 1.b. If one assumed an equal flow through the PCA's due to symmetry (i.e. left and right hemispheres demand equal posterior flow) the calculated WSS (Fig. 1.c) values would not match the WSS obtained in computations with in vivo BC's. An equal outlet pressure assumption, however, results in WSS almost identical to the one obtained with in vivo BC's. (Fig. 1.d). The equal pressure conditions result in a flow split proportional to the relative size of the outlet vessels. The distal resistance for both PCA's is likely to be equally low, since they quickly branch into smaller arteries.

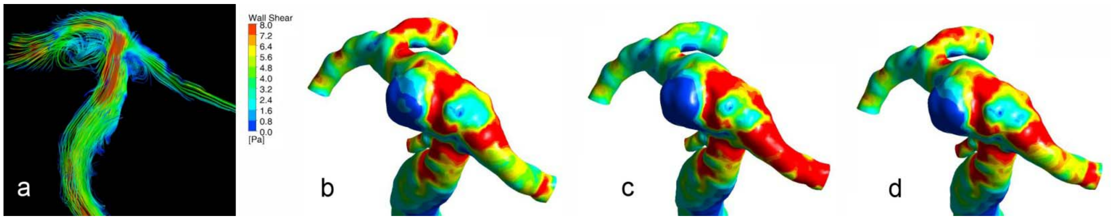

Figure 1 WSS distribution obtained for 3 outlet scenarios. (a) 4D MRV streamlines; (b) WSS from CFD with outlet flow measured with 4D MRV; (c) equal flow assumed at the outlets; (d) equal pressure assumed at the outlets.

In the second case, flow entering through the arterial segment of an AV fistula divides between the venous segment and the arterial segment distal to the anastomosis (Fig. 2). The same inlet flow was maintained in all simulations as can be seen from the matching velocities and WSS at the inlet arterial segment. The left column (a) shows the results obtained for the outlet conditions provided by in vivo MRV. An equal pressure assumption results in an extremely incorrect flow field and WSS, as most of the flow exits the distal artery rather than entering through the narrow anastomosis into the vein (Fig. 2.b). Venous circulation has substantially lower resistance than the arteries downstream, however it is difficult to prescribe realistic pressure difference between the venous and arterial outlets. Knowing that typically about 80% of the flow is diverted to the venous circulation, one can specify flow ratio at the outlets and thus obtain a reasonable approximation of the actual flow field, as shown in the right column (c). It is instructive that the in vivo 4D MRV measurements obtained for this patient have shown that in reality there is retrograde flow in the distal arterial segment for most of the cardiac cycle (as shown by the arrow). Thus, except for peak systole, the flow in the venous segment is equal to the sum of the flow measured in the proximal and distal arterial segments. Importantly, a constant outlet flow ratio based on assumptions about the typical split between the distal arteries and the venous segment would be wrong for most of the cardiac cycle.

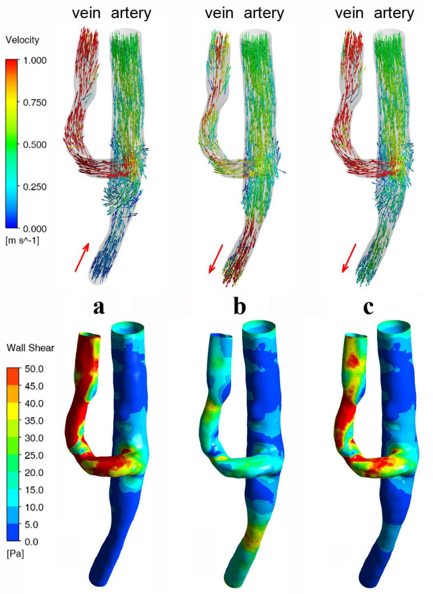

Figure 2 Velocity vectors (top row) and WSS (bottom row) obtained for 3 outlet scenarios. (a) outlet flow measured in vivo with 4D MRV; (b) equal pressure assumed at the outlets; (c) 80% of the flow exiting through the venous segment. Arrow shows the flow direction in the distal arterial segment.

These examples demonstrate that while it is possible in some cases to obtain reasonable results based on assumptions about the outlet flow or pressure values, in general the accuracy of the model should be ensured by using in vivo measurements. Acquiring 2D MRV data in all relevant inlet and outlet vessels requires prescription of 2D perpendicular slices and, since it is often difficult to determine the location and orientation of these at time of imaging, that approach is often impractical. The 4D MRV technique, however, only requires specification of a 3D volume encompassing the vessels of interest and can therefore acquire all data needed to accurately specify boundary conditions for the subsequent CFD modeling.

Conclusions

In vivo 4D MRV is the only available technique capable of measuring the flow division and thus providing patient-specific boundary conditions required for CFD modeling. This technique ensures the accuracy of the boundary conditions and reduces the effect of various modeling assumptions and uncertainties on computational results.

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